



Three-dimensional tropospheric water vapor in coupled climate models compared with observations from the AIRS satellite system

David W. Pierce,¹ Tim P. Barnett,¹ Eric J. Fetzer,² and Peter J. Gleckler³

Received 30 May 2006; revised 28 July 2006; accepted 12 September 2006; published 1 November 2006.

[1] Changes in the distribution of water vapor in response to anthropogenic forcing will be a major factor determining the warming the Earth experiences over the next century, so it is important to validate climate models' distribution of water vapor. In this work the three-dimensional distribution of specific humidity in state-of-the-art climate models is compared to measurements from the AIRS satellite system. We find the majority of models have a pattern of drier than observed conditions (by 10–25%) in the tropics below 800 hPa, but 25–100% too moist conditions between 300 and 600 hPa, especially in the extra-tropics. Analysis of the accuracy and sampling biases of the AIRS measurements suggests that these differences are due to systematic model errors, which might affect the model-estimated range of climate warming anticipated over the next century. **Citation:** Pierce, D. W., T. P. Barnett, E. J. Fetzer, and P. J. Gleckler (2006), Three-dimensional tropospheric water vapor in coupled climate models compared with observations from the AIRS satellite system, *Geophys. Res. Lett.*, 33, L21701, doi:10.1029/2006GL027060.

1. Introduction

[2] Water vapor is a major greenhouse gas expected to play a key role in future human-induced global warming [Ramanathan, 1981; Held and Soden, 2000]. Moistening of the relatively dry subtropical upper troposphere would be particularly important to the magnitude of warming obtained [Pierrehumbert, 1995; Brogniez *et al.*, 2005]. We emphasize water vapor in the upper troposphere, rather than column integrated water vapor, because even small absolute changes in the small amount of water vapor at the upper levels can have strong effects on the radiative forcing [Intergovernmental Panel on Climate Change (IPCC), 2001]. This is partly because absorptivity is proportional to the logarithm of water vapor concentration, so it is the fractional (not absolute) change in water vapor mass that determines its strength as a feedback mechanism [Soden *et al.*, 2005]; and partly because the upper troposphere is much colder than the ground, and the impact of changes in water vapor on OLR grow sharply as the difference in temperature with the ground increases [IPCC, 2001]. It is therefore important to determine how well climate models used for

projections of future climate simulate water vapor in this region.

[3] A number of recent papers have investigated this question using General Circulation Models (GCMs) [e.g., Soden and Bretherton, 1994; Bates and Jackson, 1997; Soden *et al.*, 2005; Brogniez *et al.*, 2005; Gettelman *et al.*, 2006]. In general, they found reasonable agreement between climate model simulations and observations. However, these studies have two drawbacks. First, they were limited to atmospheric GCMs forced by observed sea surface temperatures (SSTs). Specifying the correct SST may constrain the model response, especially in the lower troposphere. Second, except for Gettelman *et al.* [2006], the comparison data came from HIRS type satellite systems, which have a broad vertical sensitivity extending from roughly 700 to 100 hPa [e.g., Brogniez *et al.*, 2005]. The weighting down to 700 hPa, though small, can dominate the result since there is much more water vapor lower in the atmosphere. Other work has examined simulated humidity in models other than global GCMs [e.g., Dessler and Sherwood, 2000; Minschwaner and Dessler, 2004].

[4] Our objective in this work is to investigate the simulation of water vapor in fully coupled global ocean-atmosphere GCMs used to estimate future climate warming. We compare the models to data from a relatively new satellite system, AIRS, which has much higher vertical resolution (~2 km) than its predecessors. This allows an unprecedented test of the full three-dimensional global water vapor field in coupled models. Other techniques of examining the water vapor field, such as radiosondes or station-based GPS information [e.g., MacDonald *et al.*, 2002; Bengtsson *et al.*, 2003], generally provide good coverage only over land, although GPS radio-occultation techniques may remove this limitation. We first describe the AIRS instrument and the models, then compare the annual mean and seasonal cycle of modeled upper tropospheric water vapor with AIRS data.

2. Data

[5] The Atmospheric Infrared Sounder (AIRS) experiment, a hyperspectral infrared grating spectrometer with an accompanying Advanced Microwave Sounding Unit radiometer, is carried on the Aqua spacecraft in a sun-synchronous orbit crossing the equator southward at 0130 and northward at 1330 local time. Aqua was launched May 2002; we use monthly mean data from September 2002 through October 2005. The daily L3 (version 4) data was downloaded from the Goddard DAAC (<http://disc.gsfc.nasa.gov/data/datapool/AIRS/>) and averaged to monthly values for this work.

¹Climate Research Division, Scripps Institution of Oceanography, La Jolla, California, USA.

²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

³Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, California, USA.

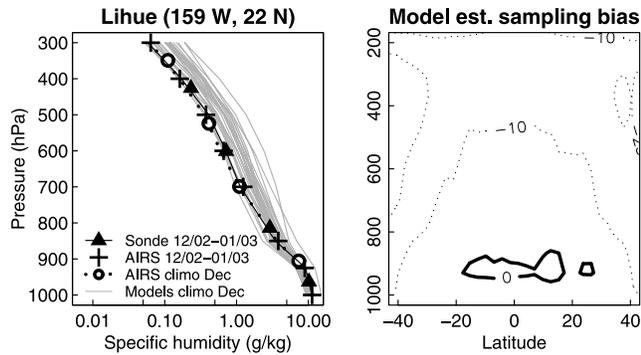


Figure 1. (left) Vertical profiles of specific humidity at Lihue. Values measured from Dec 2002 through Jan 2003 from radiosondes (triangles) and AIRS (crosses) are compared to Dec climatologies from AIRS (open circles) and various climate models (grey lines). Note that all values are at standard pressure levels, but identifying symbols have been offset for clarity. (right) Zonally averaged cloud sampling bias estimated from CCSM3 (percent), using same contour interval as Figures 2 and 3 for easier comparison. The sampling biases are generally smaller than the model-AIRS differences shown in Figures 2 and 3, implying that the differences are not due solely to sampling biases.

[6] Retrievals yield cloud fraction, cloud top pressure and temperature, surface temperature, and vertical profiles of temperature and water vapor. The measurements' vertical resolution and uncertainties are described by *Aumann et al.* [2003]. The temperature and water vapor profiles have been validated for both land and ocean for a broad range of geographic conditions (see *Divakarla et al.* [2006], *Tobin et al.* [2006], and companion papers). AIRS specific humidity profiles have RMS uncertainties of 10–30% and biases of a few percent in 2 km layers for all non-polar conditions.

[7] Retrievals can be made in the presence of non-precipitating cloud fraction up to $\sim 70\%$ [*Susskind et al.*, 2006]; a preponderance of cloudy scenes may lead to biases in the sampled climate states. *Fetzer et al.* [2006] show this sampling bias affects the AIRS total water vapor climatology $<10\%$ in the tropics and subtropics. However those results cannot be used to infer sampling biases above ~ 5 km, where $\sim 10\%$ of water vapor resides. To address this we compared AIRS measurements to 124 Vaisala radiosondes at Lihue, Hawaii for Dec 2002 and Jan 2003 (Figure 1, left), and 71 sondes at the Nauru site [see *Tobin et al.*, 2006] for Sep 2002 to Jan 2003. RMS sampling biases at Lihue and Nauru were less than 10% and 5%, respectively, up to 300 hPa. We also estimated the sampling bias using a year's worth of hourly data from the NCAR CCSM3 global coupled climate model, both fully sampled and only sampled when the 2-dimensional total

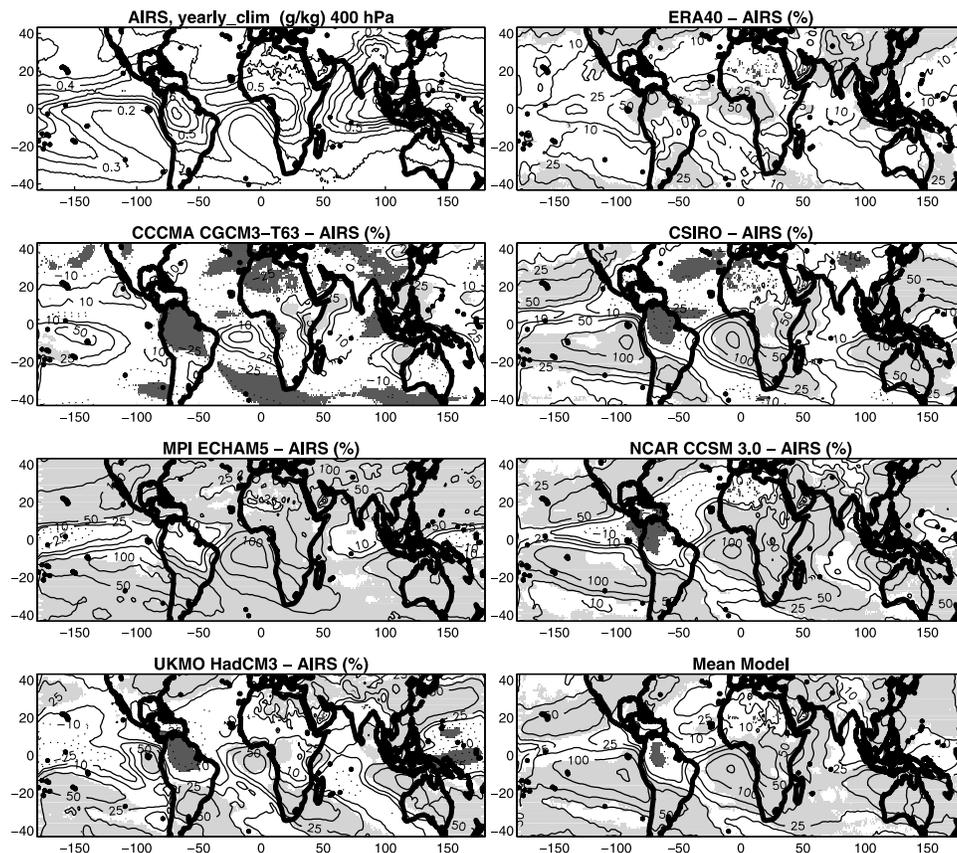


Figure 2. (top left) Yearly averaged specific humidity (g/kg) from AIRS, 400 hPa. The other plots show the difference between model and AIRS field for various models as labeled and (bottom right) for the mean model, expressed as a percentage of the AIRS field. Light and dark shading indicates where the model value is moister and drier than AIRS at the 95% significance level, respectively. Contour levels are ± 10 , 25, 50, 100, and 200 percent. The zero line is omitted.

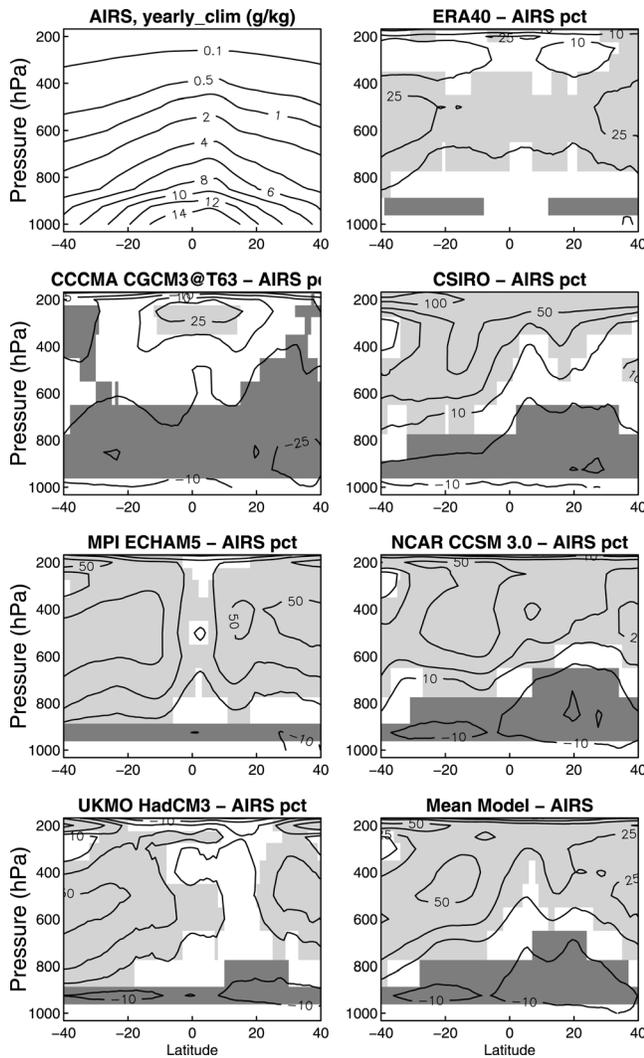


Figure 3. As in Figure 2 but for zonally-averaged data.

cloud fraction was less than 70%. The results (Figure 1, right) show the sampling underreports the humidity by <10% below 600 hPa, and 10–20% above 500 hPa. Biases due to inadequate sampling of diurnal variability using twice-daily soundings, the frequency AIRS provides, were found by *Dai et al.* [2002] to be <3% over the central U.S. Collectively, these values are considerably smaller than the biases between AIRS and the models examined in this work. The inference is that the AIRS-model differences found here are not due to sampling biases.

[8] We use climate model data from groups across the world who submitted their output to the PCMDI database, covering the period 1990–1999 to approximately match AIRS. (In coupled model experiments, there is no specific correspondence between model years and real years; we compare the statistics of the fields.) We focus here on the mean of the 22 models with monthly specific humidity data available, but also show results from NCAR CCSM3, CSIRO Mk 3, MPI ECHAM5, UKMO HadCM3, and CCCMA CGCM3-T63 to demonstrate that the mean model biases are not due to one or two extreme outliers. Descriptions of these models along with the data can be found at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php. Our results

and conclusions pertain to most or all of the models, except as noted. We also include the ERA-40 reanalysis for comparison.

[9] Results will be presented on the AIRS grid, where humidity values are the mean over the layer above the indicated level [*Olsen et al.*, 2005]. For example, values at “500 hPa” are the mean over the layer 500–400 hPa. The model results were put onto this grid by fitting a cubic spline to the log of the humidity profile, then integrating the interpolated values over the layer.

3. Results

[10] Figure 1 shows vertical profiles of specific humidity at Lihue (159°W, 22°N) from radoisondes (triangles), contemporaneous AIRS (crosses), and AIRS climatology (circles). The grey lines show model December climatologies; there is a systematic tendency for the models to be too moist above 700 hPa. In the next section we show this model error is generally found throughout the global atmosphere.

3.1. Mean Fields

[11] The mean specific humidity was computed as a function of longitude, latitude and height for both the models and AIRS. The AIRS mean field was then subtracted from the model mean fields to show where they differ. Given the short (4-yr) observed record, it is important to estimate the likelihood that differences between the model and observations arise from chance sampling fluctuations, for example by having a run of unusually moist or dry years in the particular 4 years that were observed. To this end, statistical significance was assessed by analyzing non-overlapping 10-yr blocks from each of the models’ 20th century runs over the period 1900–1989, using only model data, and employing the same process as was used to compute the AIRS-model difference (i.e., a 4-yr average minus the preceding decade’s average). Places where the AIRS-model difference falls outside the central 95% of this distribution, using the model with the widest distribution at each point (i.e. the most conservative estimate) are shaded.

[12] The results at 400 hPa (Figure 2) show the AIRS 4-yr mean specific humidity field (bottom left plot) and the difference fields expressed as a percentage of the AIRS mean field. Percentages are shown rather than absolute errors because the fractional change in water vapor controls its strength as a feedback mechanism [*Soden et al.*, 2005]. Over much of the tropics and subtropics, the mean model values (bottom right plot) are 25–100% too moist. This difference is significantly greater than expected to be seen by chance due to sampling variability (shaded regions) even given the short observed record, except in the eastern tropical Pacific, where large interannual variability is found (not shown). Since this difference is much larger than the expected AIRS errors outlined above, we conclude the problem lies with the models. The ERA-40 reanalysis (top right plot) tends to have overly moist conditions as well, but with less severity than generally seen in the coupled model runs, presumably due to the use of observations to help constrain the reanalysis.

[13] The zonal average (Figure 3) shows the specific humidity errors tend to form a dipole with overly dry

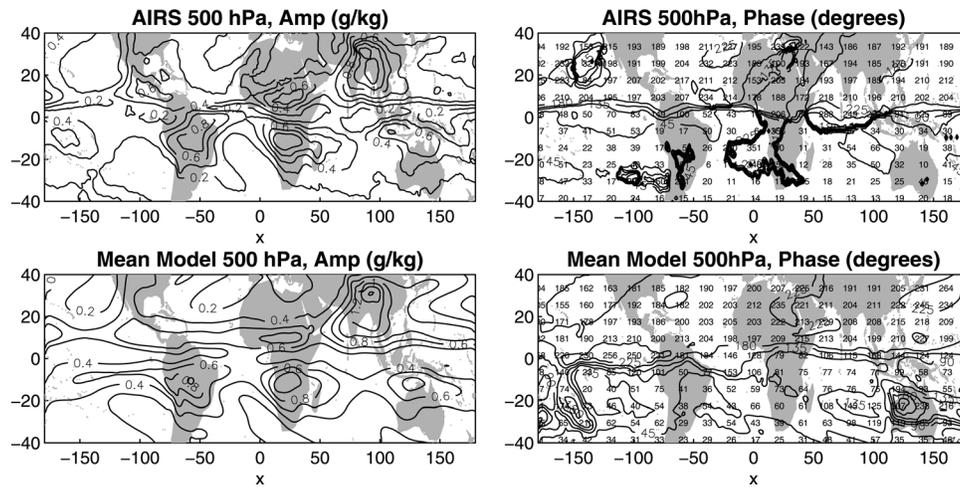


Figure 4. (left) Amplitude (g/kg) and (right) phase (degrees) of the annual cycle of specific humidity at 500 hPa (top) as observed from AIRS and (bottom) for the mean model. Phases are such that Jan = 0, Apr = 90, etc., with a contour interval of 45 degrees. Values of the phase are shown at subsampled points for easier comparison in regions where the phase is nearly constant.

conditions below 800 hPa, but overly moist conditions aloft. This structure would tend to reduce the apparent disagreement between the models and observations of column-integrated precipitable water. The ERA-40 reanalysis (top right plot) again shows errors similar to seen in the coupled model, but milder. In the model average (Figure 3, bottom right plot), and most individual models, this pattern exhibits some symmetry about the latitude of the ITCZ, which suggests a problem with the models' vertical transport of water vapor. The tendency to have greater percentage errors aloft than at the surface is consistent with this picture, since the rapid drop of humidity with altitude (Figure 3, top left) means vertical transport of a fixed quantity of water vapor across a pressure surface will have a greater percentage impact above than below. Additionally, Dessler and Sherwood [2000] point out the importance of correctly simulating the three-dimensional wind field to correctly simulating humidity at the highest altitudes considered here.

3.2. Seasonal Cycle

[14] The amplitude and phase of the best-fit annual harmonic are shown for AIRS and the model mean in Figure 4. There is reasonable agreement between the models and observations in the amplitude, and in the phase in the northern hemisphere. The models tend to have phase errors in the southern hemisphere, however. This generally holds true for the various height levels we investigated, although near the surface in some locations (such as the Amazon) the models tend to underestimate the magnitude of the seasonal cycle (not shown).

4. Discussion

[15] The results show the models we investigated tend to have too much moisture in the upper tropospheric regions of the tropics and extra-tropics relative to the AIRS observations, by 25–100% depending on the location, and 25–50% in the zonal average. This discrepancy is well above the uncertainty in the AIRS data, and so seems to be a model

problem. Even though the total column integrated water vapor profile may be nearly correct, this is an important finding for model simulations of future climate change, because even small absolute changes in water vapor in the upper troposphere can have a strong effect on radiative forcing if they are appreciable fractional changes [IPCC, 2001].

[16] The vertical distribution of the error suggests the origin of the problem may lie with the models' vertical moisture transport. A similar vertical structure of errors in relative humidity was found by Gettelman *et al.* [2006] using a single atmospheric GCM (CAM3) forced by observed SSTs; here we find this problem is symptomatic of many fully coupled climate models. Once the annual mean is removed from both data sets there is better agreement amongst their seasonal cycles, particularly in the northern hemisphere.

[17] We have examined several sampling issues to see if the satellite data could be biased by having fewer retrievals in cloudy conditions; examples are shown in Figure 1. These results, to be reported elsewhere, suggest that varying cloud cover cannot explain the discrepancies between AIRS and the models within about 40 degrees of the equator, although continuing effort on this subject is needed. The AIRS validation work [Fetzer *et al.*, 2006] also shows that a variety of other sampling issues do not appreciably influence the moisture estimates equatorward of 40 degrees.

[18] It appears the models errors are real, and so could have a number of important consequences. One critical question is whether these model errors make a substantial difference to the greenhouse warming projections for the next century [cf. Soden *et al.*, 2005]. A fixed *absolute* change in water vapor concentration in the upper troposphere due to anthropogenic effects will have a varying *fractional* change that depends on the base water vapor concentration present before the change is applied. If the models simulate this base water vapor concentration incorrectly (as we find here), then the strength of the water vapor feedback mechanism might be misrepresented. Given the importance of the water vapor feedback in determining the

magnitude of future climate change, numerical simulations addressing this question are urgently needed.

[19] **Acknowledgments.** A portion of the work described in this paper was performed by the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration. Additional support came from the LUSciD LLNL/UCSD Scientific Data Management Project. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

References

- Aumann, H. H., et al. (2003), The AIRS/AMSU/HSB on the Aqua mission: Design, science objectives, data products, and processing systems, *IEEE Trans. Geosci. Remote Sens.*, *41*, 253–264.
- Bates, J., and D. Jackson (1997), A comparison of water vapor distributions with AMIP-1 simulations, *J. Geophys. Res.*, *102*, 21,837–21,852.
- Bengtsson, L., et al. (2003), The use of GPS measurements for water vapor determination, *Bull. Am. Meteorol. Soc.*, *84*, 1249–1258.
- Brognez, H., R. Roca, and L. Picon (2005), Evaluation of the distribution of subtropical free tropospheric humidity in AMIP-2 simulations using METEOSAT water vapor channel data, *Geophys. Res. Lett.*, *32*, L19708, doi:10.1029/2005GL024341.
- Dai, A., J. Wang, R. H. Ware, and T. Van Hove (2002), Diurnal variation in water vapor over North America and its implications for sampling errors in radiosonde humidity, *J. Geophys. Res.*, *107*(D10), 4090, doi:10.1029/2001JD000642.
- Dessler, A. E., and S. C. Sherwood (2000), Simulations of tropical upper tropospheric humidity, *J. Geophys. Res.*, *105*, 20,155–20,163.
- Divakarla, M. G., C. D. Barnett, M. D. Goldberg, L. M. McMillin, E. Maddy, W. Wolf, L. Zhou, and X. Liu (2006), Validation of Atmospheric Infrared Sounder temperature and water vapor retrievals with matched radiosonde measurements and forecasts, *J. Geophys. Res.*, *111*, D09S15, doi:10.1029/2005JD006116.
- Fetzer, E. J., B. H. Lambriksen, A. Eldering, H. H. Aumann, and M. T. Chahine (2006), Biases in total precipitable water vapor climatologies from Atmospheric Infrared Sounder and Advanced Microwave Scanning Radiometer, *J. Geophys. Res.*, *111*, D09S16, doi:10.1029/2005JD006598.
- Gettelman, A., W. D. Collins, E. J. Fetzer, A. Eldering, and F. W. Irion (2006), A satellite climatology of upper tropospheric relative humidity and implications for climate, *J. Clim.*, in press.
- Held, I., and B. Soden (2000), Water vapor feedback and global warming, *Annu. Rev. Energy Environ.*, *25*, 441–475.
- Intergovernmental Panel on Climate Change (IPCC) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.
- MacDonald, A. E., Y. Xie, and R. H. Ware (2002), Diagnosis of three-dimensional water vapor using a GPS network, *Mon. Weather Rev.*, *130*, 386–397.
- Minschwaner, K., and A. E. Dessler (2004), Water vapor feedback in the tropical upper troposphere: Model results and observations, *J. Clim.*, *17*, 1272–1282.
- Olsen, E. T., E. Fishbein, S.-Y. Lee, and E. Manning (2005), AIRS/AMSU/HSB version 4.0 level 2 product levels and layers, technical report, 6 pp., Jet Propul. Lab., Calif. Inst. of Technol., Pasadena.
- Pierrehumbert, R. T. (1995), Thermostats, radiator fins and the local run away greenhouse, *J. Atmos. Sci.*, *52*, 1784–1806.
- Ramanathan, V. (1981), The role of the ocean-atmosphere interactions in the CO₂-problem, *J. Atmos. Sci.*, *38*, 918–930.
- Soden, B., and F. Bretherton (1994), Evaluation of water vapor distribution in general circulation models using satellite observations, *J. Geophys. Res.*, *99*, 1187–1210.
- Soden, B., D. Jackson, V. Ramaswamy, M. Schwarzkopf, and X. Huang (2005), The radiative signature of upper tropospheric moistening, *Science*, *310*, 841–844.
- Susskind, J., C. Barnett, J. Blaisdell, L. Iredell, F. Keita, L. Kouvaris, G. Molnar, and M. Chahine (2006), Accuracy of geophysical parameters derived from Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit as a function of fractional cloud cover, *J. Geophys. Res.*, *111*, D09S17, doi:10.1029/2005JD006272.
- Tobin, D. C., H. E. Revercomb, R. O. Knuteson, B. M. Lesht, L. L. Strow, S. E. Hannon, W. F. Feltz, L. A. Moy, E. J. Fetzer, and T. S. Cress (2006), Atmospheric Radiation Measurement site atmospheric state best estimates for Atmospheric Infrared Sounder temperature and water vapor retrieval validation, *J. Geophys. Res.*, *111*, D09S14, doi:10.1029/2005JD006103.

T. P. Barnett and D. W. Pierce, Climate Research Division, Scripps Institution of Oceanography, Mail Stop 0224, La Jolla, CA 92093-0224, USA. (dpierce@ucsd.edu)

E. J. Fetzer, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

P. J. Gleckler, Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, USA.